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New Belle results on $D^0 - \bar{D}^0$ mixing

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We report the new measurement of $D^0 - \bar{D}^0$ mixing in decays to K^+K^- and $\pi^+\pi^-$ final states that is based on the total Belle data sample of 976 fb^{-1} . The preliminary results are $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$ and $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$.

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1 Introduction

Mixing of neutral mesons occurs when the flavor eigenstates differ from the physical mass eigenstates of the meson-antimeson system. In case of D^0 mesons mass eigenstates are expressed as $|D_{1,2}^0\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, with $p^2 + q^2 = 1$. If $p = q$ the two mass eigenstates are CP-even and CP-odd; otherwise CP is violated. Charm mixing is characterized by two parameters: $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where Δm and $\Delta\Gamma$ are the mass and decay width differences of mass eigenstates, respectively, and Γ is the average D^0 decay width.

Mixing in D^0 decays to CP eigenstates, such as $D^0 \rightarrow K^+K^-$, manifests in a lifetime that differs from the lifetime of decays to flavor eigenstates, such as $D^0 \rightarrow K^-\pi^+$. The quantity

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1 \quad (1)$$

is equal to the mixing parameter y if CP is conserved. If CP is violated the lifetimes of D^0 and \overline{D}^0 decaying to the same CP eigenstate also differ and the lifetime asymmetry, defined as

$$A_\Gamma = \frac{\tau(\overline{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^+K^-)}{\tau(\overline{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^+K^-)} \quad (2)$$

becomes non-zero. The quantities y_{CP} and A_Γ are connected to the mixing parameters x and y by [1] $y_{CP} = y \cos \phi - \frac{1}{2}A_M x \sin \phi$ and $A_\Gamma = \frac{1}{2}A_M y \cos \phi - x \sin \phi$, where $\phi = \arg(q/p)$ and $A_M = 1 - |q/p|^2$.

First evidence for $D^0 - \overline{D}^0$ mixing was obtained in 2007 by Belle [2] and by BaBar [3] in two different decay modes. We report here an update of our first-evidence measurement in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$ decays using almost twice larger data set.

2 Event selection

The decays $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ are reconstructed in the decay chain $D^{*+} \rightarrow D^0\pi^+$ in order to suppress background and to tag the D^0 flavor at production. To reject D^{*+} candidates coming from B decays, we require that the D^{*+} momentum measured in the center-of-mass system (CMS) of the e^+e^- collisions be greater than 2.5 GeV/c; for a fraction of data taken at $\Upsilon(5S)$ we increase this threshold to 3.1 GeV/c.

Besides using our standard kaon and pion selection criteria, based on dE/dx , threshold aerogel Cherenkov counters and time-of-flight, and vertex fits, we select D^0 candidates using two kinematic variables: the invariant mass of the D^0 decay products M and the energy released in the D^{*+} decay $q = (M_{D^*} - M - m_\pi)c^2$. The proper decay time of the D^0 candidate is calculated from the projection of the vector joining

the two vertices, \vec{L} , onto the D^0 momentum vector: $t = m_{D^0} \vec{L} \cdot \vec{p}/p^2$, where m_{D^0} is the nominal D^0 mass [4]. The decay time uncertainty σ_t is evaluated event-by-event from the error matrices of the production and decay vertices.

The sample of events for the lifetime measurements is selected using ΔM , Δq and σ_t . These selection criteria are optimized on Monte Carlo (MC) simulation by minimizing the statistical error on y_{CP} . Background is estimated from sidebands in M ; the sideband position has also been optimized in order to minimize the systematic uncertainty. The yields of selected events are 242×10^3 (K^+K^-), 114×10^3 ($\pi^+\pi^-$) and 2.61×10^6 ($K^-\pi^+$), with signal purities of 98.0%, 92.9% and 99.7%, respectively.

3 Lifetime fit

By studying the proper decay time distribution of $D^0 \rightarrow K^-\pi^+$ decays we observe a significant dependence of its mean value on $\cos \theta^*$, where θ^* is the D^0 CMS polar angle. Using MC simulation we find that the generated proper decay time distribution of selected events agrees well in each $\cos \theta^*$ bin with an exponential distribution and that the lifetime is consistent with the generated value. The observed dependence is thus due to the resolution function offset that depends on $\cos \theta^*$. Therefore, to reduce systematic uncertainties arising from the resolution function parameterization the measurement is performed in bins of $\cos \theta^*$; an additional requirement $|\cos \theta^*| < 0.9$ is imposed to suppress the events with the largest offsets (about 1% of events).

The fitting procedure in each $\cos \theta^*$ bin is similar to the one used in our previous measurement [2], where we performed a binned simultaneous fit to KK , $K\pi$ and $\pi\pi$ samples. The resolution function is constructed similarly, from normalized distribution of σ_t using a double or triple Gaussian PDF for each σ_t bin. The widths σ_k^{pull} and fractions w_k of these Gaussian distributions are obtained from fits to the MC distribution of pulls $(t - t_{\text{gen}})/\sigma_t$. The procedure is repeated for each $\cos \theta^*$ bin. The parameterization reads:

$$R(t) = \sum_{i=1}^{n_{\text{bin}}} f_i \sum_{k=1}^{n_g} w_k G(t; \mu_i, \sigma_{ik}), \quad (3)$$

where $G(t; \mu_i, \sigma_{ik})$ represents a Gaussian distribution of mean μ_i and width σ_{ik} , and f_i is the fraction of events in the i -th bin of the σ_t distribution. The mean and width are parameterized as:

$$\sigma_{ik} = s_k \sigma_k^{\text{pull}} \sigma_i \quad \mu_i = t_0 + a(\sigma_i - \sum_{j=1}^n f_j \sigma_j) \quad (4)$$

where s_k , $k = 1, \dots, n_g$ are the width scaling factors for each of the n_g Gaussian's, t_0 is the resolution function offset, and a is a parameter to model a possible asymmetry of the resolution function. The parameters s_k , t_0 and a are free parameters in the fit.

The proper decay time distribution is parameterized with

$$f(t) = \frac{N}{\tau} \int e^{-t'/\tau} R(t-t') dt' + B(t), \quad (5)$$

with the following free parameters: N , τ , s_k , t_0 and a . A sideband subtracted σ_t distribution is used to construct $R(t)$. The term $B(t)$ describes background and is fixed with a fit to the sideband distribution.

Background is parameterized as a sum of two lifetime components, a component with zero lifetime and a component with an effective lifetime τ_b :

$$B(t) = N_b \int [f\delta(t') + (1-f)\frac{1}{\tau_b}e^{-t'/\tau_b}] R_b(t-t') dt' \quad (6)$$

The background resolution function $R_b(t)$ is assumed to be symmetric ($a \equiv 0$) and is composed of three Gaussian's with $s_3 = s_2$. The fraction f of zero-lifetime component is found to be $\cos \theta^*$ dependent; its value is fixed in each bin using MC simulation. The parameters t_0 , s_1 , s_2 and τ_b are determined from a fit to sideband distribution summed over $\cos \theta^*$ bins. However, the shape in individual bins remains bin-dependent since σ_t distribution, f and N_b depend on $\cos \theta^*$.

To extract y_{CP} and A_Γ the decay modes are fitted simultaneously in each $\cos \theta^*$ bin using a binned maximum likelihood fit. The parameters shared between decay modes are y_{CP} and A_Γ (KK and $\pi\pi$), t_0 and a (all decay modes) and parameters s_1 , s_2 and s_3 up to an overall scaling factor. The fit has been tested with the generic MC simulation equivalent to six times the data statistics. The fitted y_{CP} and A_Γ are found to be consistent with the input zero value and the fitted $K\pi$ lifetime τ is found to be consistent with the generated value. A linearity test performed with MC simulated events re-weighted to reflect different y_{CP} shows no bias.

4 Results

The experimental data were taken with two different silicon vertex detector (SVD) configurations: for the first 153 fb^{-1} a 3-layer SVD was used, while for the rest of the data a 4-layer SVD was used. We treat both running periods separately, since the resolution function differs.

The proper decay time distributions are fitted simultaneously as discussed in the previous section. The results of the fits are shown in Fig. 1. Fit confidence levels (CL) are above 5% (except one with CL=3.3%) and are distributed uniformly *. The plots in Fig. 1 are obtained by summing the histograms and functions in all fitted

*We use Pearson's definition of χ^2 and take only the bins with the fitted function greater than one.

$\cos \theta^*$ bins. The residuals show no significant structure. The normalized Pearson's χ^2 are 1.01 (SVD1) and 1.16 (SVD2).

Fig. 2 shows the results of the fits in bins of $\cos \theta^*$ for y_{CP} , A_Γ and the $D^0 \rightarrow K^- \pi^+$ lifetime τ . The average is obtained by a least square fit to a constant. We find $y_{CP} = (1.11 \pm 0.22)\%$, $A_\Gamma = (-0.03 \pm 0.20)\%$ and $\tau = (408.46 \pm 0.54)$ fs, where the errors are statistical only. The results for individual running periods are consistent with each other. The measured D^0 lifetime is also consistent with the current world average [4].

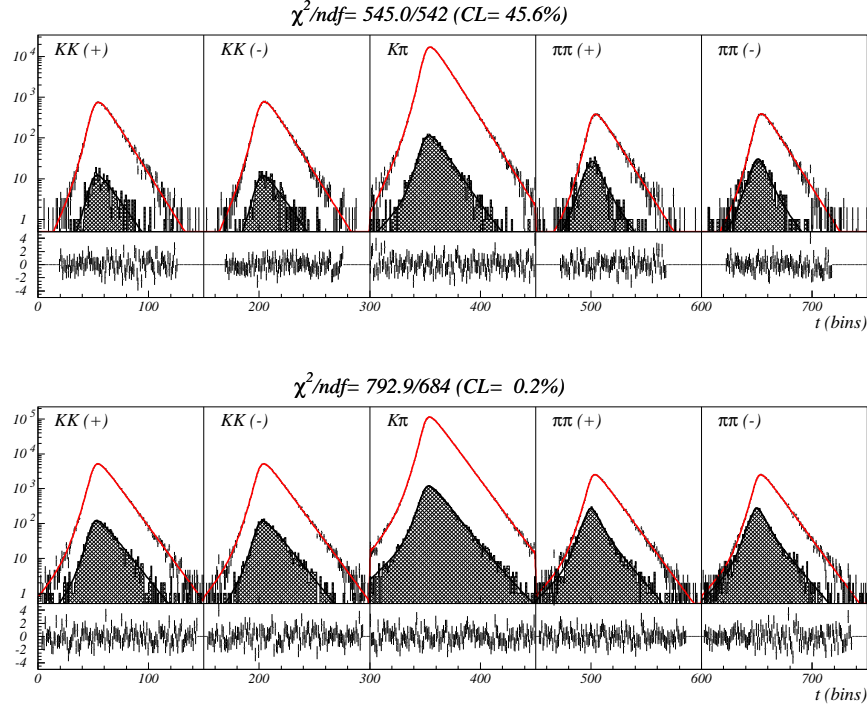


Figure 1: Simultaneous fit of SVD1 (top) and SVD2 (bottom) proper decay time distributions. The plots show a sum of distributions and fitted functions (in red) over $\cos \theta^*$ bins; the residuals are plotted beneath. The signal-region distributions are shown as error bars and the sideband-region distributions as hatched histograms. The “(+)” and the “(-)” denote the charge of the tagging slow pion.

5 Systematics

The systematic uncertainties are summarized in Table 1. The largest contribution is found to arise from possible SVD misalignments. The impact of misalignments has been extensively studied using a special signal MC simulation with different local and

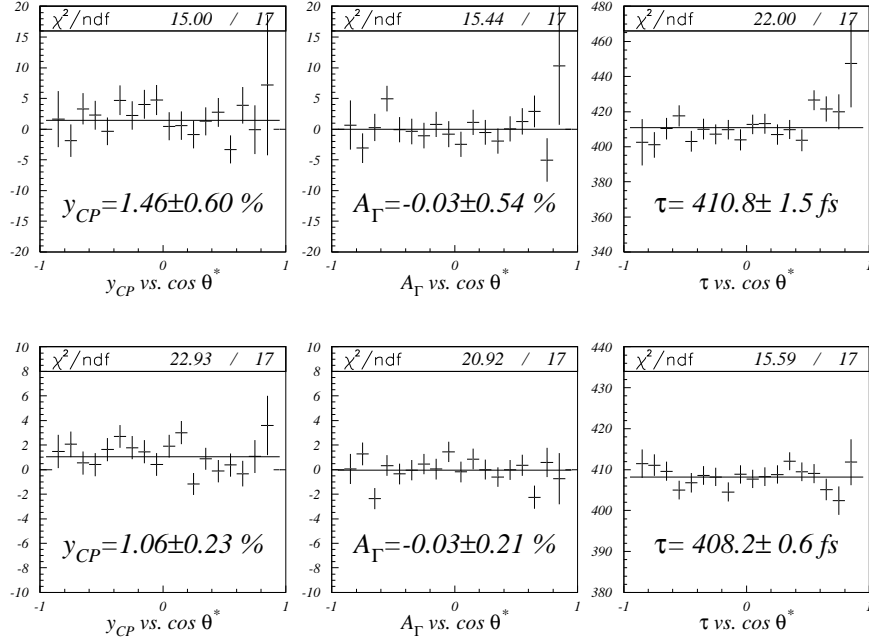


Figure 2: Results of simultaneous fits in bins of $\cos \theta^*$ (points with error bars) for SVD1 (top) and SVD2 (bottom). The horizontal line in each plot is a least square fit of constant to data points.

global SVD misalignments. We find that the SVD misalignment affects the resolution function considerably, especially its offset t_0 , and it can explain the differences seen between MC and data. However, the effect on the resolution function is very similar for KK , $K\pi$ and $\pi\pi$ decay modes, and thus mainly cancels when relative lifetime measurements such as y_{CP} and A_Γ are performed.

Other sources of systematics arise from possible impact of selection criteria to the acceptance, from the position of mass window ΔM , from background parameterization and from background statistical fluctuations, from resolution function parameterization and from binning in t and $\cos \theta^*$. The total systematic uncertainties are estimated to 0.11% for y_{CP} and 0.08% for A_Γ .

6 Summary

With the full Belle data set of 976 fb^{-1} , we obtain the preliminary results

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%, \quad (7)$$

$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%, \quad (8)$$

Table 1: Systematic uncertainties

source	Δy_{CP} (%)	ΔA_{Γ} (%)
acceptance	0.050	0.044
SVD misalignments	0.060	0.041
mass window position	0.007	0.009
background	0.059	0.050
resolution function	0.030	0.002
binning	0.021	0.010
sum in quadrature	0.11	0.08

where the first error is statistical and the second is systematical. The significance of $y_{CP} \neq 0$ is 4.5σ when both errors are combined in quadrature, and 5.1σ if only the statistical error is considered. The result for A_{Γ} is consistent with no indirect CP violation. Both results are in good agreement with our previous measurement [2] as well as with the BaBar measurements in the same decay modes [5, 6].

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